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Spectroscopy of arcs in the rich cluster Abell 963

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SUMMARY

Spectra are presented for portions of the two arcs observed close to the dominant cD galaxy in the rich cluster Abell 963 ($z = 0.206$). The spectrum of the northern arc displays a strong emission line at 6600 Å which is seen along the entire arc. The feature cannot be understood unless the redshift is greater than that of the cluster, the most likely interpretation being [O II] 3727 Å at $z = 0.771$. The southern arc is considerably fainter and its spectrum shows no obvious features. However, new CCD photometry is consistent with a near-constant blue colour ($B - R \sim 0.3$) along both arcs supporting the suggestion that they arise from the gravitationally lensed light of a background object. The optical and infrared colour is consistent with a spiral galaxy undergoing strong star formation at this redshift. We discuss briefly the implication of this result, and the possible role lensing surveys may play in the study of high-redshift galaxies.

1 INTRODUCTION

The spectroscopic confirmation that some of the giant arcs seen in a number of moderate-redshift clusters are indeed gravitationally lensed background objects (e.g. Soucail *et al.* 1988, 1990) opens up a new tool in observational cosmology. Traditionally, the only way of studying objects with redshifts $z > 1$ has been via absorption line spectroscopy of QSOs or the use of rare (and possibly atypical) classes of radio galaxies. By using rich clusters as *gravitational telescopes* we can determine information on the high-redshift population of galaxies unobtainable any other way (Fort *et al.* 1988). Furthermore, since the objects are lensed only because they happen to lie serendipitously behind a totally unrelated cluster, selections effects should be minimal; this is an important consideration in a subject plagued by such problems.

In a separate paper (Smail *et al.*, in preparation) we discuss the feasibility of objectively cataloguing extended arc-like features by application to a sample of rich clusters. One important goal is a determination of the redshift distribution of faint galaxies from the rate of occurrence of arcs of different forms (Ellis 1990). On the lensing hypothesis, giant features such as the arcs in Abel 370 and Cl 2244 − 02 (*cf.* Paczyński 1987; Miller & Goodrich 1988) are expected to be significantly rarer than small distortions (Nemiroff & Dekel 1989). The latter 'arclets' have so far largely been identified on the basis of their colours using subtraction techniques (Fort *et al.* 1988; Tyson, Valdes & Wenk 1990).

Although it seems secure that *giant* arcs such as that in Abell 370 and Cl 2244 − 02 arise from gravitational lensing, it may be premature to assume that *all* arcs and arclets arise in this way. A difference in colour between the arc and the cluster ellipticals is not, by itself, convincing enough to support the lensing interpretation. For example, objects significantly bluer than the cluster ellipticals could, in general, lie at any redshift including, of course, that of the cluster itself. Edge-on galaxies are an obvious possibility which can only be excluded via spectroscopy. A further class of possible interlopers are the arcs seen close to the central galaxies of certain rich clusters. Although blue examples again exist, many might be shell-like features physically associated with the dominant galaxy (Malin & Carter 1980).

Thus although existing spectroscopy for giant arcs supports the lensing hypothesis in many cases (Fort 1990; Pellò *et al.* 1990), it is important to continue spectroscopic follow-up for the more difficult arclets and the centralized arcs before assuming that *all* apparently distorted features in deep cluster images represent lensing examples. In this paper we discuss new spectroscopic observations of two arcs in the rich cluster Abell 963, which are nearly symmetrical about the central cD galaxy and typical of those of this class.

2 PHOTOMETRY

The two arcs in the rich cluster Abell 963 ($z = 0.206$) were first noted in B and R CCD frames taken by Lavery & Henry (1988, hereafter LH). In fact, the arcs are just visible in earlier SIT Vidicon data published by Butcher, Oemler & Wells (1983, hereafter BOW). A recent composite $B + R$ CCD image of the cluster core taken on the 2.5-m Isaac

Newton Telescope (INT) is shown in Fig. 1(a) and a colour-subtracted ($B-R$) composite scaled to make the cD envelope disappear is shown in Fig. 1(b). The contrast of the blue arcs is striking.

LH commented on the fact that the arcs are both substantially bluer ($B-R \simeq 0.6 \pm 0.1$) than the cluster ellipticals ($B-R \simeq 2.5$) and near-concentric about the central cD. At the time of publication, A963 represented the first example of an arc and counter arc in a single cluster. LH concluded that the most likely mechanism responsible for the arc pair is gravitational lensing of a single high-redshift galaxy by the cD and cluster core.

Photometry is clearly important in determining whether the arc and counter-arc arise from the same background source. Unfortunately, due to the faintness of the features and the proximity of the cD envelope this is not straightforward. Although LH determined mean arc colours, they did not examine colours for their individual portions. This is particularly important for the southern arc which might be contaminated by unrelated objects. For convenience we label these portions in Fig. 1(b). It is for this reason we secured new B and R images referred to above. These were service observations taken on the prime focus of the 2.5-m INT with an RCA CCD on 1990 April 17 in 1.6 arcsec seeing. Although conditions were not photometric, our relative photometry can be calibrated to the precision required using the colour-magnitude relation of 14 early-type cluster members and colours of the cD envelope (both assuming a redshifted spectral energy distribution of a present day L^* elliptical; $B-R=2.47$), and LH's colour for BOW object #238. These zero points differ by less than 0.1 mag in $B-R$.

Since the arcs are embedded in the envelope of the cD, it is necessary to consider carefully how to determine the background when deriving colours. LH determined the background level from an equivalent portion of the image obtained by *reflection* about the centre of the cD. This method can only be applied to the S arc since the mirror image of the N arc falls on another galaxy. Using this method we can reproduce LH's colour for the S arc but believe it

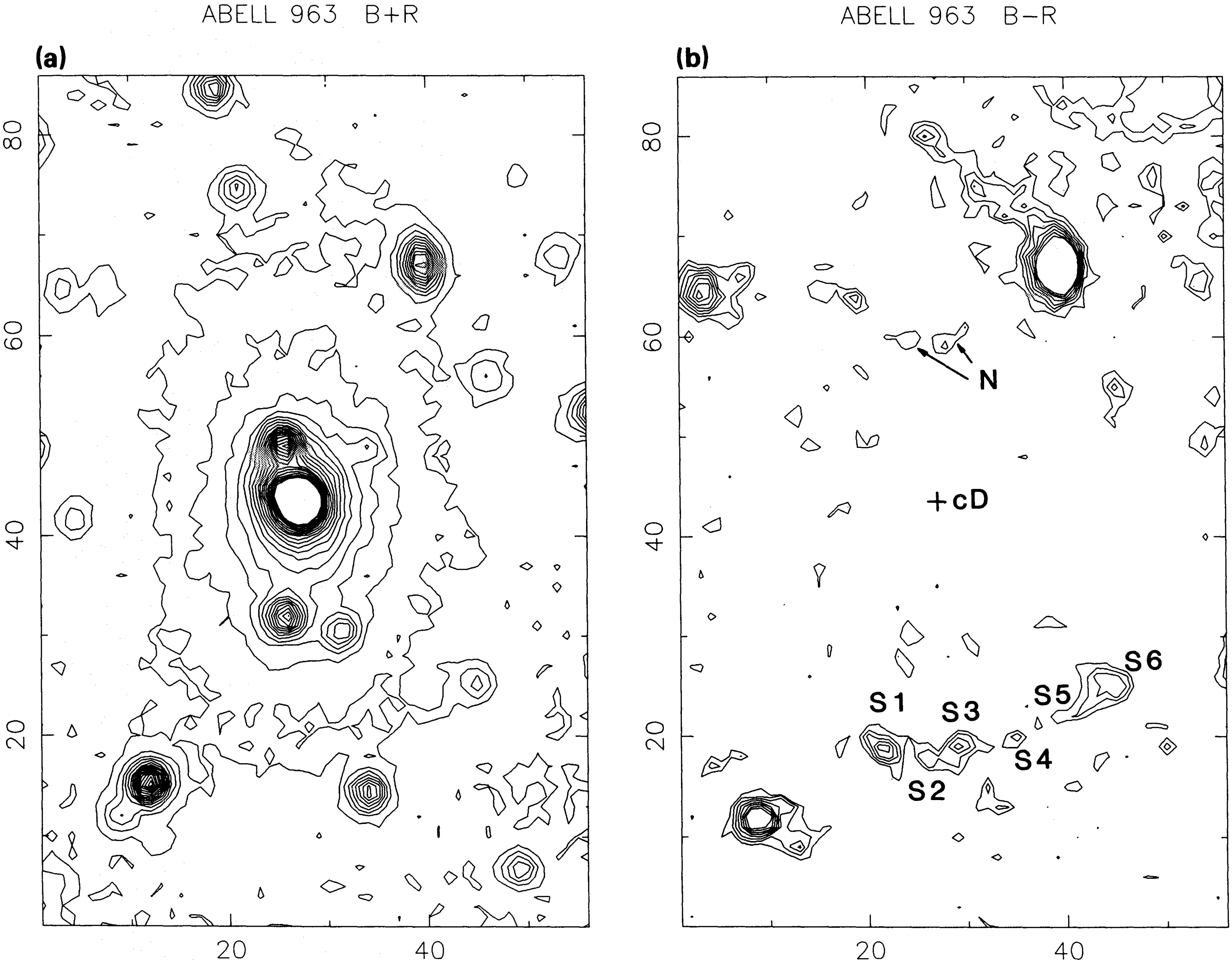


Figure 1. (a) Composite $B+R$ CCD image of the field of Abell 963 with the intensity in each band scaled to be equal for the centre of the cD galaxy. North is up and east is to the left. The field is 41×64 arcsec^2. (b) Composite $B-R$ image with the intensity in each band scaled so that the cD envelope has zero intensity in this plot. The field orientation and size is the same as in (a). The cD galaxy is marked with a cross, the northern arc by N and the individual sub-components of the S arc as S1–S6. BOW's object #238 is S6.

assumes unnecessarily that the envelope is circularly symmetric. Instead, we determined the background in the vicinity of both arcs by linear interpolation between regions immediately inside and outside the arcs along a radius from the cD centre; unless the variation of $B-R$ with radius in the cD envelope is non-linear, this should give a more realistic estimate of the background.

Table 1. Arc photometry.

Object	B–R This paper	LH
N arc	$0.3^{+0.8}_{-0.8}$	0.5
S arc (S1–S3)	$0.3^{+0.3}_{-0.4}$	0.7
S1	$0.7^{+0.2}_{-0.3}$	
S2	$0.1^{+0.6}_{-0.8}$	
S3	$-0.4^{+0.4}_{-0.5}$	
S5	$0.5^{+0.3}_{-0.3}$	
S6(BOW 238)	$1.7^{+0.1}_{-0.1}$	
cD	2.47	

Our results for the N arc and various portions of the S arc are summarized in Table 1. The mean colours ($B-R\simeq 0.3$) are slightly bluer than LH's and, except for S4 for which we could not obtain a reliable colour because of contamination of the background by a nearby galaxy, both arcs are consistent with a single colour. The variations across the S arc (e.g. at the western end) are probably not significant. Despite the large photometric uncertainties (± 0.3–8 mag), the low probability of unrelated objects having colours so remarkably blue in a crowded field of red ellipticals, strongly suggests both arcs are related to the same phenomenon.

Table 2. Details of observations.

Instrumental Setup

Instrument	4.2m WHT + ISIS + 800 × 1180 EEV CCD
Dispersion	124 Å mm^{-1}, 2.72 Å pixel^{-1}, 8 Å resolution
Slit format	264 arcsec × 1.5 arcsec
Wavelength range	4800 – 7800 Å
Spatial resolution	1 pixel ≡ 0.33 arcsec

Observing Log

Date	Seeing (arcsec)	Source	Slit PA	Exposure (s)
20 Feb 1990	0.8	A963 North arc	90	12,000
20 Feb 1990	0.8	A963 cD	0	1,500
21 Feb 1990	1.0	A963 South arc	87	13,000

3 SPECTROSCOPY

During 1990 February 20–21, we secured spectra for the two arcs (N and S) using the ISIS spectrograph on the 4.2-m William Herschel Telescope (WHT); the observing configuration and log is summarized in Table 2.

Fig. 2 shows the integrated light profiles derived from the spectra (without sky subtraction) for the three position angles secured on the WHT. From the spectrum obtained intersecting both arcs (Fig. 2a) the arc signals are found to be about 25–30 per cent of the cD envelope at that radius. This is in broad agreement with surface-brightness values derived from LH's photometry; they claim both arcs have surface brightnesses $\mu_R \simeq 25.0$ mag arcsec^{-2} which represents about 2 per cent of a typical La Palma dark sky. For the N arc a similar estimate is derived using the spectrum along the arc

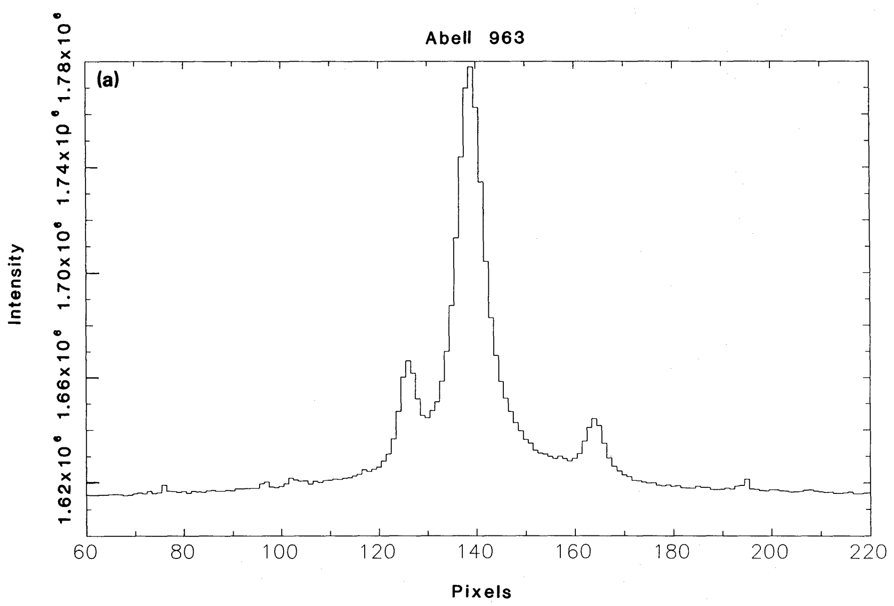
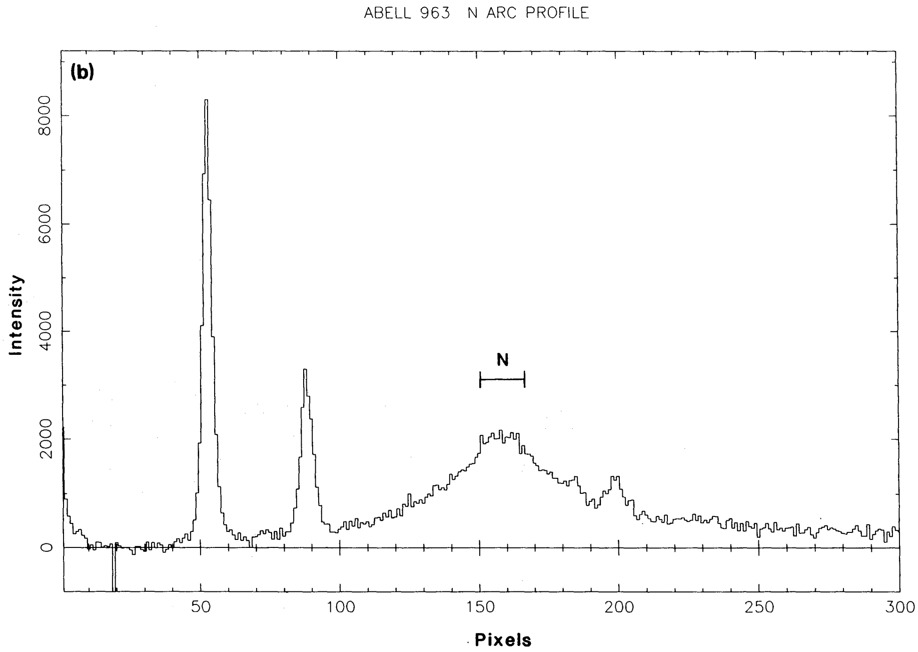


Figure 2. Sky-brightness profiles derived from the spectral data with objects marked as in Fig. 1: (a) slit position angle intersecting both arcs; (b) along N arc; (c) along S arc.



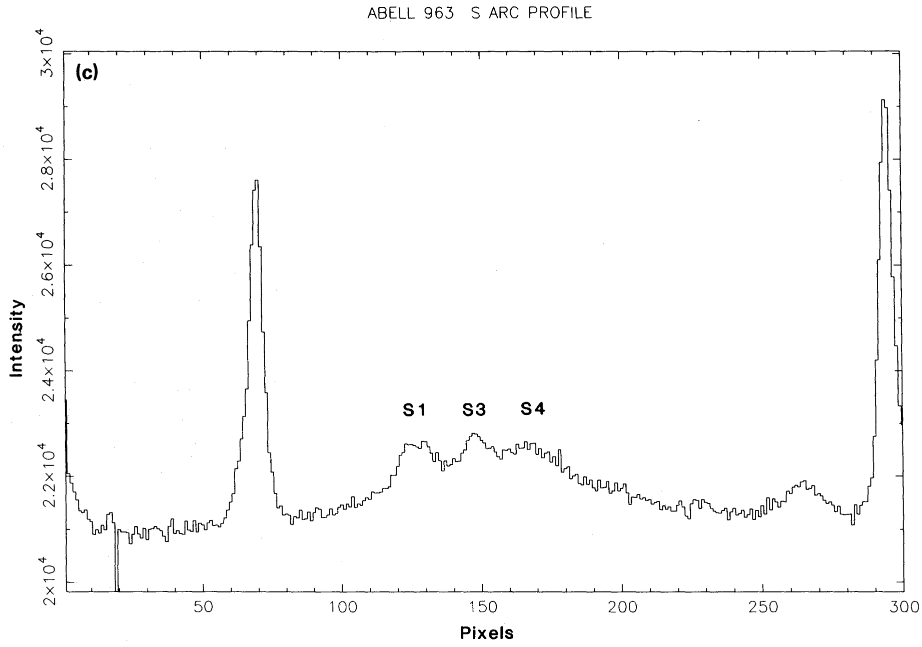


Figure 2 – *continued*

where an extent of ≃ 5 arcsec is found (Fig. 2b) in agreement with Fig. 1(a). The profile of the S arc (Fig. 2c) shows evidence for three objects which we identify with S1, S3 and S4. S2 and S5 did not fall on the slit.

For the N arc, spectral extraction was confined to the portion marked in Fig. 2(b) and sky-subtraction performed using parabolic interpolation from adjacent regions. The resulting spectrum has a single strong emission line at 6600 Å (Fig. 3) but no other obvious features. To demonstrate that this line comes from the arc rather than from a superimposed object, or bad sky subtraction, we show the sky-subtracted *image* in the vicinity of the arc in Fig. 4. The emission line clearly extends along the full length of the arc but no further.

Given the presence of only a single feature, a reliable redshift is hard to justify. However, to support the lensing hypothesis it is sufficient to demonstrate, first, that the light is consistent with that from a single object (as is clearly the case – Fig. 4), and secondly, that the object is background to the cluster. If the light was due to a source foreground to the cluster, the only likely identification for the line at 6600 Å would be Hα at $z=0.0056$. Given the blue colour one would expect to see Hβ at 4888 Å. Additionally, the object would

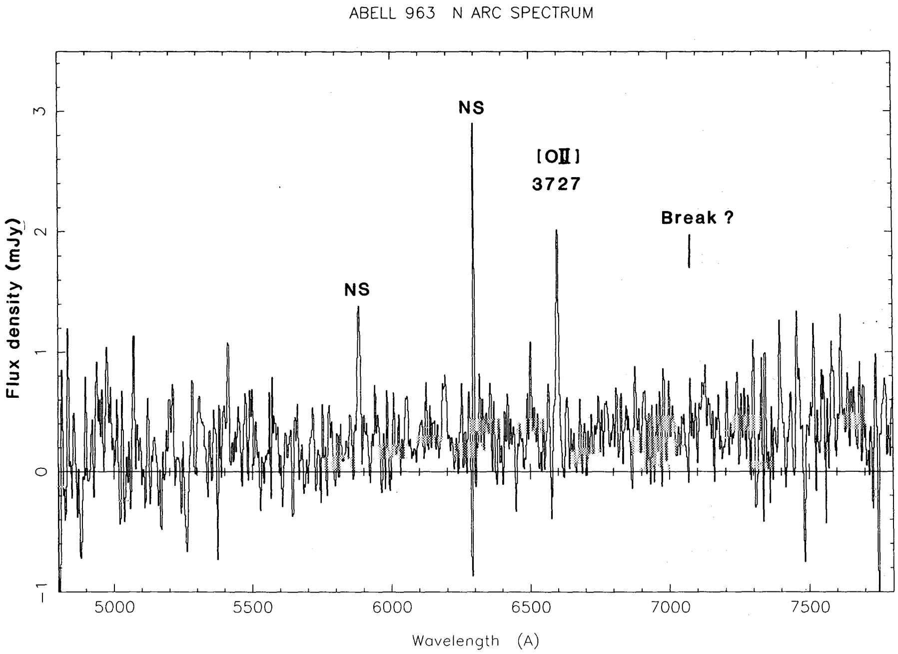


Figure 3. Sky subtracted spectrum of the N arc in Abell 963 with features marked at the deduced redshift of $z=0.771$. Imperfectly subtracted night sky lines are marked 'NS'.

only be 4 h^{-1} kpc across. This hypothesis is thus very unlikely.

At the cluster redshift itself, the line has no sensible identification at all. If the line is [O III] 5007 at $z=0.318$, the absence of Hβ and [O III] 4959 is puzzling, as is the absence of Hγ for this colour if the strong line is Hβ at $z=0.358$. Most probably the line is [O II] 3727 at $z=0.771$ in which case no other strong emission lines would be expected in the 4800–7800 Å window. The most likely additional feature expected for a galaxy of this colour would then be the Balmer line Hε plus Ca II H at $\lambda_{\rm rest}=3968$ Å, for which there is marginal evidence. Higher redshift identifications cannot be ruled out, but in each case one would expect to see other lines or discontinuities present.

The identification of the N arc with a background object, most likely at $z=0.771$, was determined from a quick reduction of the spectrum on the night of its observation. This prompted examination of the S arc on the following night. This spectrum is not so satisfactory for several reasons. First the weather, whilst good, was not as exceptional as on the previous night. Secondly, the arc is fainter and curved. We found no evidence for the line found in the N arc in any spatial subset of the S arc. Neither did we find evidence for any other spectral feature. Further spectroscopic work on the S arc is highly desirable but would benefit from a purpose-made curved slit.

4 DISCUSSION

We can place some limits on the source if we assume that both arcs are gravitationally lensed images of a background object at $z=0.771$ with $B-R\simeq 0.3\pm 0.5$ (Table 1). This average colour is somewhat bluer than that expected from redshifted spirals. Even the bluest Sdm/Irr galaxies today (fig. 12 of Colless *et al.* 1990) would have $B-R>1$ for all redshifts of interest, $z<2$.

In the case of the giant arc in Abell 370, spectroscopically confirmed to be a lensed source at $z=0.72$ (Soucail *et al.* 1988), Aragón Salamanca & Ellis (1990) showed, via a strong detection at K (2 μm), that its optically blue colour probably arises from a relatively mild ultraviolet (UV) upturn in an otherwise normal Sbc spiral. Could the blue $B-R$ colours in A963 reflect a burst of star formation in an otherwise old system?

The A963 arcs are considerably bluer than the giant arc in Abell 370 but a detection at 2 μm would clearly indicate the presence of an old population. Because of the lower surface brightness and the overwhelming presence of the cD envelope at infrared (IR) wavelengths, this is a very difficult observation. Fig. 5 shows the result of a 5-hr integration undertaken in 1990 May using UKIRT's IRCAM. Interestingly, a 1.5 σ detection of the N arc may be secured at a mean surface brightness contour of $\mu_{\rm K}\simeq 22.0$ mag arcsec^{-2}. The implied $R-K\sim 3.5\pm 0.6$ would support the presence of a strong starburst population in an otherwise normal spiral; the very blue colour contrasting with a fairly average $R-K$ at this redshift. Clearly more accurate photometry is desirable before the overall spectral energy distribution is modelled further. Given the faintness and location of the arcs this will, however, be very difficult.

Such blue optical colours are typical of a sizeable fraction of the faint field population (Tyson 1988) and it is tempting to assign the lensed source to this population. The faintest redshift surveys (Colless *et al.* 1990) already show such galaxies at modest redshifts ($z<0.6$), thus the probability of lensing one in the interval $0.5<z<1$ must presumably be quite high, particularly if as seems likely the mean UV surface brightness of such sources is raised as a result of the strong burst of star formation.

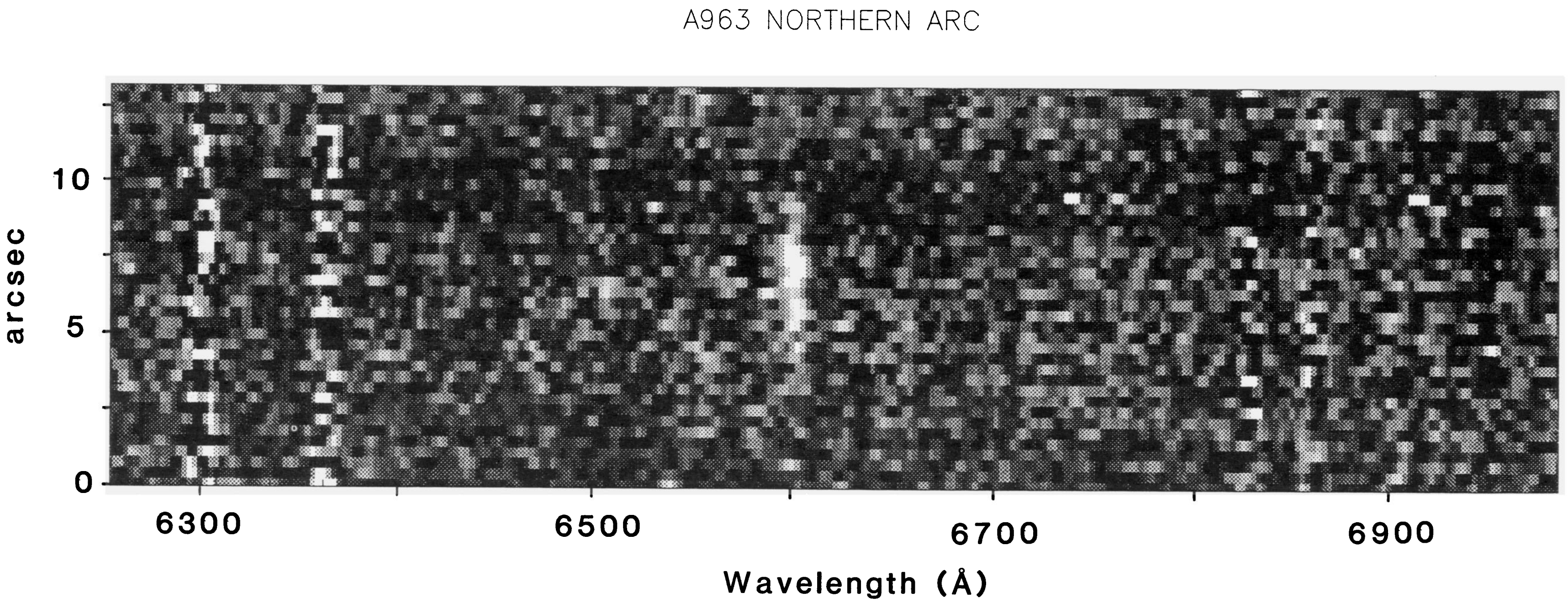


Figure 4. Sky subtracted two-dimensional spectral image for the region of the slit containing the N arc. Each pixel is 0.33 arcsec $\times$ 2.72 Å. The emission line at 6600 Å extends along just that portion of the slit occupied by the arc in Fig. 2(b).

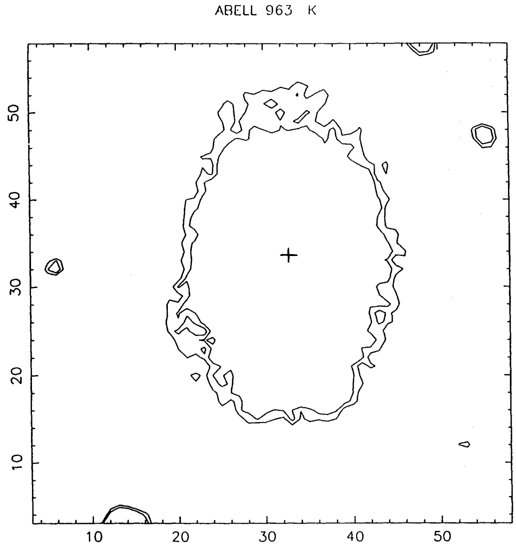


Figure 5. IR 2-μm image of the A963 cluster core displayed to reveal the detection of the N arc at a contour of $\mu_K = 22.0$ mag arcsec^{-2}. The field is 36 × 40 arcsec^2 with the same orientation as in Fig. 1. The centre of the cD galaxy is marked with a cross.

The presence of strong star-forming galaxies at $z \sim 0.5$–1 is not unexpected in many evolutionary pictures including those invoking recent galaxy formation. However, the detection of a few examples implies little about any general increase in the star formation rate for the *overall* galaxy population without some consideration of the selection processes involved. The same biases which render a galaxy visible in the redshift surveys (*cf.* Broadhurst, Ellis & Shanks 1988; Colless *et al.* 1990) are quite likely to affect the detection of arcs in surface-brightness-limited surveys (Smail *et al.* 1990). A proper understanding of the means by which arcs are deteced and a statistical study of their rates of occurrence is required to properly exploit this interesting phenomenon in unravelling the properties of high-redshift galaxies.

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